LCA Methodology

A Method to Include in LCA Road Traffic Noise and its Health Effects

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Abstract

Background, Aims and Scope. Transport noise represents an environmental problem that is perceived by humans more directly than the usual chemical emissions or resource uses. In spite of this, traditional LCA applications still exclude noise – probably due to the unavailability of an appropriate assessment method. In order to fill the gap, this article presents a study proposing a new computational procedure for the determination of health impairment resulting from noise emissions of road vehicles.

Main Features. The magnitude of health impairment due to noise is determined separately for each vehicle class (cars, trucks,..) and is calculated per vehicle-kilometre driven during the day or at nighttime on the Swiss road network. This health impairment is expressed in cases of sleep disturbance or communication disturbance, and furthermore aggregated in DALY (Disability Adjusted Life Years) units representing the number, duration and severity of the health cases. The method is modelling the full cause-effect chain from the noise emissions of a single vehicle up to the health damage. As in some other modern concepts of environmental damage assessment, the analysis is subdivided into the four modules of fate analysis, exposure analysis, effect analysis and damage analysis. The fate analysis yielding the noise level increment due to an additional road transport over a given distance is conducted for transports with known or with unknown routing, the latter case being more important in LCA practice. The current number of persons subject to specific background levels of noise is determined on the basis of the road traffic noise model, LUK, developed by the Swiss canton of Zurich. The number of additional cases of health impairment due to incremental noise is calculated with data out of the Swiss Noise Study 90. An assessment of the severity of sleep disturbance and communication disturbance, in comparison to other types of health impairment, was performed by a panel consisting of physicians experienced in the field of severity weighting of disabilities.

Results and Discussion. The quantities of health cases and of DALY units are given per 1'000 truck or car kilometres on Swiss roads, and the range of the confidence interval is estimated. A plausibility check is made by a quantitative comparison of the results with health damage due to traffic accidents in Switzerland, and with health damage due to traffic noise in the Netherlands.

Conclusions and Outlook. The method is ready for use in LCA practice. However, the temporary solution for transports outside of Switzerland should be replaced by feeding country specific data into the fate and exposure model. Further, a comparable assessment for rail transport would facilitate decisions on road or rail transport. A decisive element of transport noise assessment is the availability of robust links between noise level and medical conditions. Whilst the number of the corresponding studies is sufficiently large, a design for better pooling of study results is desirable.

Keywords: Communication disturbance; DALY; disability adjusted life years; dose-effect characteristics, exposure-response relationship; interference with speech communication; noise effects; road traffic noise; sleep disturbance; vehicle noise

1 Background, Aims and Scope

Noise is a type of environmental emission leading to adverse effects on a large percentage of the human population. Whilst noise from stationary equipment is mostly kept enclosed by building walls, noise from mobile equipment (road vehicles, aircraft, railways) propagates into the surroundings. Noise is generally acknowledged to be a severe annoyance to as much as 20–30 % of the population in many European countries, whereby road noise is seen to clearly demonstrate the highest share of people affected (Eurostat 1995:288–289). Further, it is clear that this noise does not merely produce temporary annoyance, but is a cause of lasting health impairments (WHO 2000:20–35, UBA 2003).

In spite of this, most LCA case studies so far neglect the impacts of noise: if processes to be analysed include a road transport activity, a typical LCA would only include the motor's chemical emissions and energy consumption. The reasons for this neglect are mainly the unavailability of appropriate noise assessment methods (Guinée 2000:68–69), as well as the opinion that noise effects are very local and difficult to interpret in relation to other impact categories (Gorree 2000:26). However, a remarkable attempt to assess noise effects in LCA (Lafleche 1997) was made for the case of car and truck transports on the highway from Milan to Bologna: In this report, the number of persons currently living beyond legal noise thresholds is counted, and the result is imputed to the single vehicles participating in the current traffic.

This article describes a recently published method (Müller-Wenk 2002) for a quantitative assessment in LCA of noise impacts on human health originating from road vehicle noise. An adaptation to rail noise is planned.

The method starts out from the following data: transport distance in km, quantity transported, category of vehicle, time (day/night) and country of transport. The LCA user can normally made available such data for the direct components and materials entering into his functional unit, whilst the data can be derived for preliminary products from accessory information given by generic LCI databases. The numerical result produced by the method is the number of cases per relevant type of health impairment, suitable as midpoint category indicator. In addition, the health damage is also expressed in aggregable DALY (Disability Adjusted Life Years) units, a well known health damage indicator at endpoint level.

2 The Cause-effect Chain of Road Vehicle Noise

There is a tendency in modern LCA methodology to link the various types of emissions to their consequences by means of cause-effect chains and with respect to human health im-

pairments. The procedure for building up the links of the cause-effect chains is comparatively well known in the case of toxic gas emissions:

1. First chain link: **fate analysis** describes the increase of the pollutant concentration in the environment, caused by the emission quantity of the toxic substance as registered in the LCI of the functional unit;
2. Second chain link: **exposure analysis** shows how many people are affected by such changes in concentration of the toxic substance, and to what extent;
3. Third chain link: **effect analysis** describes the incremental effect on health that is likely to occur if humans are exposed to a certain concentration increase of the substance during a certain period;
4. Fourth chain link: **damage analysis** describes the total extent of damage to human health that is represented by the above-mentioned health effects.

This concept for chemical emissions may also be applied to noise emissions, whereby the pollutant concentration is replaced by the time-averaged level of noise. However, the situation with noise is more complex than that with substances. First, the reverberation time of a sound is very short in comparison to the life time of the usual toxic chemicals, so that the resulting noise level from all sources varies heavily in time and from location to location. It is therefore difficult to determine the noise level at the ear of every individual and the contribution of a single source to this noise level. Second, the dependence of health impairment upon a given level of noise is substantially conditioned by structural elements of the noise as well as by the circumstances of life and the attitudes of the persons involved. The variance of noise effects from person to person is therefore larger than in the case of toxic substance effects.

The corresponding noise-specific problems – complicating the development of a cause-effect chain from road vehicle noise to health damage – are approached here by the following procedures:

A) Instead of the actual physical noise, the energy-equivalent continuous sound-pressure level LAeq,T , averaged over all daytime or nighttime hours of period T (= 1 year), is used for representing the real noise situation at a given location. LAeq averaged over 1 year is the most common acoustical measure and a reasonably adequate indicator of the complex phenomenon of a real noise – although other acoustical measures may be preferable for expressing specific noise structures in the context of specific health impairments.

B) The current noise background situation for each surface element of a geographical region is calculated by available computer models on the basis of recorded traffic densities and road/terrain properties. Combining this with maps of residential structures yields the current distribution of the population over the different noise levels, expressed in LAeq.

C) The assessment of the noise effects due to an additional journey of a road vehicle is made depending on the available routing information: If the precise routing of the vehicle's journey is known, procedure B) can be repeated with the current traffic frequencies increased by 1 unit on all roads actually used by the vehicle. The comparison of the two calculations according to B) then yields the tiny shift of the population distribution towards higher noise levels due to the vehicle's journey. This shift to higher noise levels concerns only the fraction of population that lives along the vehicle's route. If information on the precise routing of the journey is unavailable, the procedure is different. The journey is then interpreted not as an isolated local event but rather as a contribution to the annual traffic increase over the whole regional road network. Consequently, the calculation carried out does not express the actual physical noise increase along the vehicle's unknown route, but rather a calculational noise increase over the whole road network during a full year. Obviously, this calculational increase of the year-averaged noise level is extremely small. On the other hand, it relates to the whole road network and not only to a few roads.

D) The additional number of health cases due to a noise increase is calculated on the basis of dose-effect characteristics. These are developed from social surveys or epidemiological research. This increase of health effects has the format 'additional cases per unit of noise (LAeq) increase'. As noise may cause various types of health effects; an aggregation of these health effects into a total damage can be accomplished by weighting the various health impairments.

Consequently, the cause-effect chain of road transport noise – developed here for the purpose of life-cycle impact assessment – has the structure of **Fig. 1.** It is important to notice that the concept according to Fig. 1 does not require any knowledge on the vehicle's exact routing, but it can use the corresponding information if available. In LCA practice, information on the precise route of a road transport (and of the vehicle's return to its starting point) is mostly not available, e.g. because transports are combined for better use of the vehicle's loading capacity and drivers adapt the routes according to momentaneous traffic situations. An assessment procedure for unknown routes is therefore necessary. Surprisingly, the calculation of the 'calculational' noise increase of a transport without routing information is much simpler than the calculation of the actual noise increase of a transport with a precisely known routing, as the following sec-

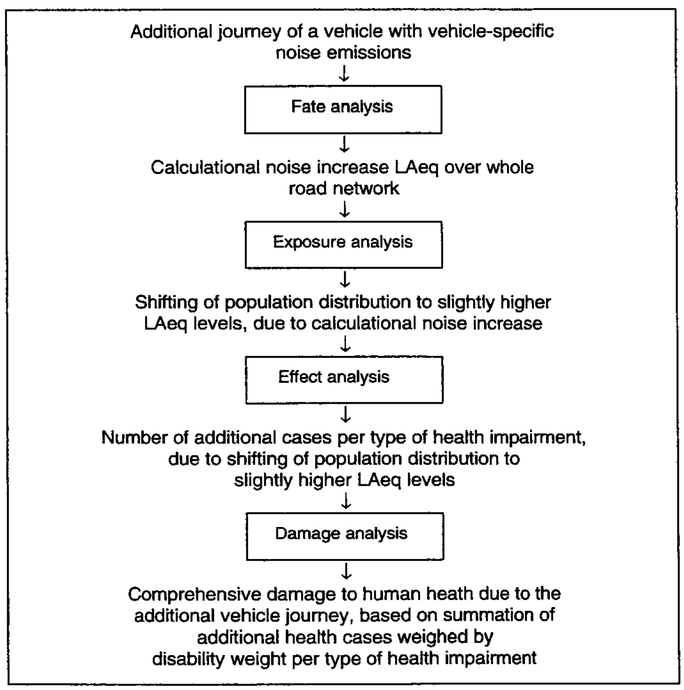


Fig. 1: Cause-effect chain for road transport noise

tions will demonstrate. In consequence, the former may be preferred even where precise routing is available from the life-cycle inventory. This text therefore focuses on the case of road transports without routing information.

In the following sections, the four modules of the analysis according to Fig. 1 will be developed for the case of the Swiss road network. In addition, comments will be given regarding the application of the concept to other European countries.

3 Fate Analysis in Detail

Several noise models are available which calculate the year-averaged noise level LAeq of a road, starting from data on the average number of vehicles per vehicle type, the average speeds and the properties of the road (gradient, type of surface). In a second step, such models also calculate the noise attenuation between road axis and the facades of buildings located in the proximity of the road, so that the noise level LAeq can be determined at the outside of any building. In Switzerland, the model according to **Fig. 2** is used most widely.

According to Fig. 2, the noise level of the road LAeq is composed of the car noise LE1 and the truck noise LE2. The truck noise LE2 depends on the traffic volume of the trucks N2, on their average speed V2, and the slope of the road i.

Such noise models can be used to calculate the actual noise level on roads on the basis of current traffic quantities N1 (cars) and N2 (trucks). However, they also are suitable for the calculation of the tiny noise level increase DeltaLeq caused by the increase by 1 unit of the average hourly number of vehicles on a road. A practical way to do this is to calculate LAeq first with N1+1 cars per hour, and then with N1+0 cars, whereby the difference of these two LAeq values yields the value of DeltaLeq. **Table 1** shows such calculations for 5 examples of Swiss roads with different traffic and road properties.

Input variables:

- N1 Average number of Type 1 vehicles (cars, vans, light motorcycles) per hour
- N2 Average number of Type 2 vehicles (trucks, buses, tractors, heavy motorcycles) per hour
- V1, V2 average vehicle speed in km/h
- i gradient of road in %

Simplifying assumptions:

- N1 + N2 are higher than 100 vehicles/hour (will be revised later)
- Road surface is normal asphalt
- No. of vehicles is the same in both directions of a road

Calculation of annual mean LAeq at a point +1 metre from the centreline of the road:

$$LAeq = 10 \times \log(10^{0.1 \times LE1} + 10^{0.1 \times LE2})$$

where:

$LE1 = E1 + 10 \times \log(N1)$

$LE2 = E2 + 10 \times \log(N2)$

$E1 = \max\,[\{12.8 + 19.5 \times \log(V1)\}, \{45 + 0.8 \times (0.5 \times i - 2)\}]$

$E2 = \max\,[\{34 + 13.3 \times \log(V2)\}, \{56 + 0.6 \times (0.5 \times i - 1.5)\}]$

Fig. 2: Calculation of average annual LAeq on a road, as described in (SAEFL 1991)

Table 1: Examples of calculations of increases in sound level for additional traffic during the day

	Calculation of increase in LAeq				
Place	Bümplitz	Saignelegier	Soyhieres	Oberentfelde	Schwägalp
Road	Bernstr	Rte de l'Hop	Rte de Bale	Aarauerstr	Passhöhe
INPUT DATA					
N1 cars/h DAY	1626	166	232	246	53
N2 trucks/h DAY	153	10	45	14	9
v speed km/h	50	60	60	60	60
i gradient of road %	2	0	0	0	0
A type of surface	0	0	0	0	0
K1 correction factor	0	0	0	0	0
INTERMEDIATE VALUES					
E'1	45.9299151	47.4739494	47.4739494	47.47394938	47.4739494
E"1	44.2	43.4	43.4	43.4	43.4
E1	45.9299151	47.4739494	47.4739494	47.47394938	47.4739494
E'2	56.5963011	57.6494116	57.6494116	57.64941163	57.6494116
E"2	55.7	55.1	55.1	55.1	55.1
E2	56.5963011	57.6494116	57.6494116	57.64941163	57.6494116
LE1	78.0411205	69.6750303	71.1288292	71.38330045	64.7167081
LE2	78.4432154	67.6494116	74.1815368	69.11069199	67.1918367
RESULTS in dB(A)					
Leq	81.2571198	71.7895633	75.9283595	73.40428387	69.1385644
LE1 if N1 +1car	78.0437906	69.7011141	71.1475086	71.40091892	64.797887
LE2 if N2 +1truck	78.4715083	68.0633385	74.2769899	69.41032422	67.6494116
Leq if N1 +1car	81.2583933	71.8056113	75.9345543	73.41535513	69.1680661
Leq if N2 +1truck	81.2719436	71.9538227	75.9924335	73.51820093	69.436344
DeltaLeq N1 +1car	**0.00127**	**0.01605**	**0.00619**	**0.01107**	**0.02950**
DeltaLeq N2 +1truck	0.01482	0.16426	0.06407	0.11392	0.29778

An inspection of Table 1 shows that DeltaLeq for 1 additional car per hour circulating on a road varies within wide limits (bold type): The noise increase DeltaLeq is small for a main road with high traffic volume (Bümplitz), whilst it is 23 times higher for the least important road of the table (Schwägalp). Remote by-roads with a few vehicles per hour only would progressively show increasing DeltaLeq values. In addition to traffic density, DeltaLeq for 1 additional car per hour is also influenced by average vehicle speed and by road properties, but this influence is less important in practice.

Due to this strong dependency on background traffic densities of the DeltaLeq for 1 additional vehicle per hour, it seems to be impossible to determine a meaningful noise increase DeltaLeq, if exact routing of this vehicle is not known.

A solution for this problem can be found if the transport to be assessed is not considered as an isolated single event, but rather as a tiny part of the yearly increase of the traffic density over all portions of the road network of a region or country. Statistics show that the yearly traffic increase of individual roads – as a first approximation – is proportional to the traffic level of the preceding year: If a road with 100'000 vehicles per day gets an annual increment of 2000 vehicles per day, the corresponding increment for a minor road with a daily circulation of 1000 vehicles would only be 20 vehicles. In reality, this is not entirely true: the traffic increase from year to year, in percent of previous year, is generally higher on main roads connecting large cities than on by-roads in the country side. Further, new roads deviate traffic from neighbouring roads so that during some time the former show traffic increases above average, the latter below average. Nevertheless, it is an admissible approximation to consider annual traffic increases of individual roads as proportional to their pre-existing traffic volume. Proportionality of traffic increase to pre-existing traffic volumes on all elements of the road network means that the annual total of additional vehicle-kilometres is spread over the whole road network according to the traffic distribution of the past year.

It is logical to proceed the same way with the amount of vehicle-kilometres required for a product to be assessed by LCA, if the routing of the corresponding transport is unknown: Instead of an arbitrary choice of a route, it is more adequate to stretch these vehicle-kilometres over the whole road network of the corresponding region or country. This way, the transport is seen as part of the annual traffic increase, and its environmental effects can be determined on the basis of this annual traffic increment.

But how can one now calculate the noise increase LAeq over the whole regional road network, as caused by 1000 vehicle-kilometres of an LCA case, spread over this network? Table 1 gives access to the answer. If Table 1 contained – instead of the 5 roads – all 1-km segments of all roads of the network, it would be possible to split up these 1000 vehicle-kilometres to all road segments in proportion to their hourly vehicle frequencies. Consequently, the number of cars or trucks per hour would increase by a tiny percentage. The DeltaLeq of the last two rows of Table 1 could then be recalculated, replacing the increase of +1 car or truck by the tiny increase proportional to each road segment's past traffic frequencies. The surprising result would then be that the corresponding DeltaLeq show only small differences between road segments, these differences being mainly due to different vehicle speeds and road gradients. In fact, if traffic increases on every road are taken as proportional to the pre-existing traffic volume, calculations as well as theoretical considerations (see Müller-Wenk 2002:22–26) show that the calculational noise increase DeltaLeq is roughly constant over all road segments of the network, with minor differences being attributable to different vehicle speeds and road surface properties. In fact, the DeltaLeq of N+1 vehicles per hour is roughly proportional to the first derivative of logN, which is proportional to 1/N. But if the traffic increase on every road segment is proportional to N instead of a constant +1 vehicle, the corresponding DeltaLeq is proportional to N*1/N, that is to say, independent of N and therefore equally high for low traffic roads and high traffic roads. The results of these calculations can be seen in **Table 2**.

Table 2: Calculational noise increase LAeq, averaged over 1 year, for the entire Swiss road network, resulting from an additional journey of 1000 km on an unknown route

Additional journeys on the Swiss road network	Noise increase DeltaLeq in micro-dB(A)
1,000 km Type 1 vehicle (cars, vans, small motorcycles), daytime	0.050
1,000 km Type 1 vehicle (cars, etc.) nighttime	0.86
1,000 km Type 2 vehicle (trucks, buses, tractors, heavy motorcycles), daytime	0.50
1,000 km Type 2 vehicle (trucks, etc.) nighttime	8.4

It is plausible that the noise increase due to a truck journey (as shown in Table 2) is about 10 times higher than in the case of a car journey, because trucks are noisier. It is also plausible that the noise increase due to a vehicle's circulation is substantially higher at nighttime than during daytime, because traffic at night is much lower so that one additional vehicle counts more than during the day with its high traffic volumes. As mentioned before, DeltaLeq is the increase of noise level LAeq averaged over a full year, and this (calculational) increase pertains to the totality of the Swiss road network. It is therefore obvious that the noise increase due to 1000 vehicle-kilometres must be extremely low, and is not expressed in decibels, but rather in millionths of decibels (micro-dB). Let's recap that the noise increase is 'calculational' insofar as it is not the noise increase due to a vehicle's physical journey that could be measured by an instrument along the route used; it is rather the calculational contribution of this single journey to the yearly increase of traffic noise over the whole road network.

The attractiveness of the result shown in Table 2 lies in the fact that the noise increase pertains to every road of the road network, due to the principle of stretching the 1000 vehicle-km over the whole network in proportion to pre-existing traffic frequencies. This greatly simplifies the following step of the exposure analysis: The noise increase is burdening the whole population of the region, and it is not necessary to split up this population into sub-populations per road.

One could object here that the buildings are not immediately adjacent to the roads in general, so that a noise attenuation takes place between the road and the location of the building. This objection is correct, but it is important to notice that noise attenuation between the noise source and the location of noise impact is a function of geometry and materials only, and it does *not* depend on the noise level of the noise source (see SAEFL 1991:12). In other words, the amount of a noise increase DeltaLeq stays unchanged on its way from the noise source to the point of the noise impact. This is not in contradiction with the fact that a given DeltaLeq causes a smaller health effect if occurring at the low noise level of a building far away from the road, this aspect being dealt with in the effect analysis (see section 5).

4 Exposure Analysis in Detail

The objective of the exposure analysis is to determine the number of people being exposed to a certain increase of time-averaged noise level. In the light of the preceding comments, the very simple result of the exposure analysis is the total number of Switzerland's inhabitants, roughly 7.1 million of people.

In fact, this is the population living along or between any of the roads that constitute the Swiss road network. However, some people live so far away from public roads that the road noise does not have any kind of impact on them. Although the noise increases DeltaLeq according to Table 2 arrive at their houses too, this noise increase builds up at low noise levels of 40 dB or less, so that neither noise nor noise increase produce an adverse effect on human organisms. It is therefore a useful preparatory work for section 5 to determine here the repartition of Swiss population with respect to the exposure to time-averaged road noise.

For the time being, the officially published Swiss data on numbers of inhabitants per level of noise (BFS 2002:185) are rather old and not very reliable. To obtain better data quality, the computer-based road noise model available for the Kanton of Zurich (covering approximately 1/6 of Swiss population) was used to calculate the corresponding data with updated traffic figures, and the result for Zurich was extrapolated for the total of the Swiss population. **Fig. 3** gives a graphical representation of the data generated, indicating the year-averaged noise levels LAeq outside the buildings at nighttime (22.00–06.00). Similar data were generated for daytime.

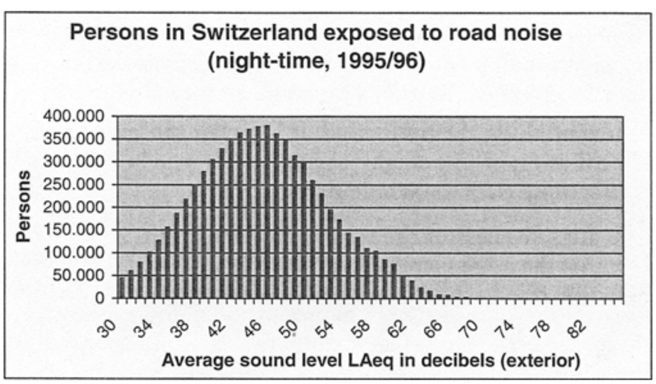


Fig. 3: Swiss population's exposure distribution to road noise (year-averaged LAeq, nighttime, 22.00–06.00, outside of building), extrapolated from LUK Zurich data. (Daytime figures are approx. 9 dB higher)

Fig. 3 represents the road noise background situation in Switzerland. Additional traffic activities cause tiny noise increments DeltaLeq according to the data of Table 2, which penetrate to the outsides of the buildings where the persons of Fig. 3 live. This means that the population segment concerned is shifted slightly to the right: Each column of Fig. 3 generates a tiny overflow to the next column at its right side. Although such noise increase may not be audible, the subsequent effect analysis will show that noise effects are allocatable to these DeltaLeq.

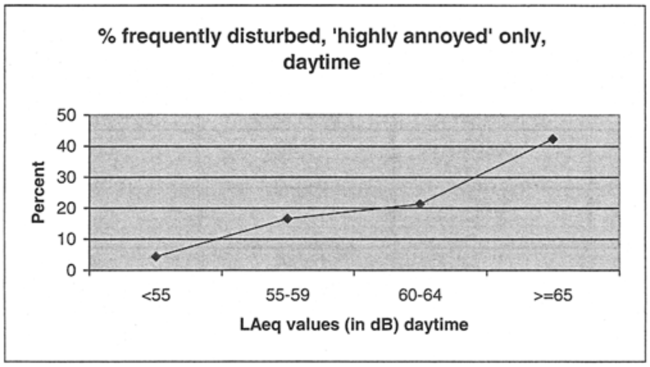
5 Effect Analysis in Detail

Noise is recognised to provoke several types of adverse health effects: hearing impairment, interference with speech communication, sleep disturbance, cardiovascular and physiological effects, mental health effects (WHO 2000:20–30). Where health in the strict sense is not impaired, people can nevertheless get annoyed by noise. A loss of working capacity may be a consequence of such primary noise effects.

Focusing here on road noise, we can exclude the effect to hearing organs and mental health effects, because these appear to be caused by higher noise levels than those transmitted from roads to nearby buildings. In general, people are unable to notice a connection between noise and cardiovascular/physiological effects so that the corresponding relationship has to be based on epidemiological research, where the detected associations are weak or inconsistent so far (WHO 2000:29). We therefore exclude the corresponding effects here, although they were modelled in (Müller-Wenk 2002:42,56). In contrast, the connection between road noise and speech communication or sleep disturbance is obvious for the affected persons as well as for the medical specialists. The effect analysis here therefore concentrates on sleep disturbance and communication disturbance. Although many people need to sleep during the daytime (06.00–22.00), and many people communicate during nighttime (22.00–06.00), the simplification is made here to associate sleep disturbance to nighttime noise, and communication disturbance to daytime noise.

Undoubtedly, sleep disturbance of a certain intensity and duration is a serious health impairment justifying the intervention of doctors or hospitals (sleep clinics). In contrast, communication disturbance is not a health impairment in the strict sense, because the affected person would have no problems to hear speech or music in the absence of noise. But as the affected persons in practice cannot escape from the noise because financial or other restrictions make a change to a quiet apartment impossible, they are comparable to a person with damaged hearing organs: the communication with other persons or acoustical equipment has deteriorated. The masking of auditory signals by the external noise is *equivalent to* a defect of the auditory organs. We therefore consider communication disturbance as a health impairment in the wider sense here.

The relationship between sleep/communication disturbance and the level of road noise has been the object of many social survey studies: People were asked to what extent they experience – due to road noise penetrating into their rooms – problems with sleeping-in or awakenings, or with listen-



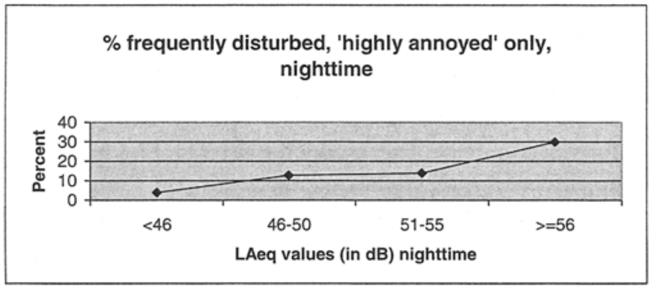


Fig. 4: Percent of interviewees per LAeq-class who declared to be disturbed every day or every few days with respect to sleep (nighttime) or communication (daytime). LAeq level is outside of buildings. Data from Swiss Noise Study 90

ing to partners or to equipment like television, telephone or recorders. In parallel, a measurement or a calculation of the road noise level LAeq outside of their building facade was made. Although the answers of a single interviewee may be distorted (intentionally or unintentionally), social surveys interviewing a sufficient number of persons are appropriate to produce reasonably reliable data. Most social survey studies in connection with road, air and rail noise ask the interviewees to express their degree of annoyance caused by the noise. In addition to this, a study with 2000 interviewees made in Switzerland in year 1991 (Oliva 1998) asked explicit questions about the frequency of their sleep-in and sleep interruption problems, as well as concerning the frequency of their problems to understand speech and to enjoy music. The noise level LAeq outside of the most exposed facade of the building was calculated but not communicated to the interviewees. The corresponding dose-effect relationships are shown in **Fig. 4**.

The lower part of Fig. 4 refers to nighttime and gives the percentage of interviewees reporting frequent and serious sleeping problems due to road traffic noise at night. It is very possible that certain interviewees put the blame on noise, although something else was the real reason for their sleep disturbance. However, it is remarkable that the percentage of disturbed persons at nighttime rises steadily from 4% at a noise level of below 46 decibels to 30% at locations where the noise level is above 55 decibels. This supports the assumption that the increasing noise level is the essential cause to which the increasing percentage of sleep complainers is attributable. Although the lowest and the highest point of the dose-response relationships of Fig. 4 refer to open classes, and although the apparent non-linearity of these curves is justifiable (Müller-Wenk 2002:39), we take the simple conclusion from the lower part of Fig. 4 that the approximate percentage of persons declaring themselves to suffer from sleep disturbance increases linearly by 1.7 percentage points per one additional dB, starting at a nighttime outdoor LAeq of 46 dB. This slope of 1.7% per dB LAeq compares reasonably well with the slopes of other studies (Maschke et al. 2001), despite the fact that those studies indicate noise levels in the form of peak measures (LAmax or SEL) and not in the form of energy-equivalent averages (LAeq). Further, the starting level of LAeq 46 dB compares well with the WHO guideline value of LAeq 45 dB (recommended noise level outside facade of bedrooms) for prevention of sleep dusturbance (WHO 2000:45). The results of a Japanese social survey (Kabuto 2002), using averaged LAeq and not peak levels, and measuring the LAeq near to the sleeper's ear by a personal sound exposure recorder, are in reasonable conformance with the Swiss data: Complaints in Japan to be woken up by road traffic noise start at a threshold LAeq of 34 dB (at sleeper's ears), and the fraction of complainers increases by 1.44 % per one additional dB. The analysis of the correlation between the noise level outside the building and at a sleeper's ears of Kabuto's Japanese sample resulted in a regression line of LAeq at sleeper's ears = 0.96 LAeq outside building – 9.7 dB, which means that LAeq at the sleeper's ears was roughly 10 dB lower than LAeq outside building. This means that the findings (Kabuto 2002) are reasonably similar to the Swiss results (threshold level LAeq 46 dB outside building, and slope 1.7% sleep disturbance per one additional dB).

The upper part of Fig. 4 shows the percentage of interviewees reporting frequent and serious communication problems due to road traffic, depending on the LAeq level at daytime. The conclusion drawn from this communication disturbance curve is that the approximate percentage of persons declaring themselves to suffer from communication disturbance increases linearly by 2.5 percentage points per one additional dB, starting at a daytime outdoor LAeq of 55 dB.

This result of the effect analysis is shown in **Table 3**. Row 4 of Table 3 gives the number of additional disturbance cases per one additional dB above threshold level, for sleep disturbance at nighttime and for communication disturbance at daytime. Instead of showing additional cases per 100 persons per 1 dB above threshold level, the result is expressed in additional cases per 1 million persons per noise increase of 1 micro-dB. This matches more conveniently with the results of the fate analysis in row 1 of Table 3, being expressed also in micro-dB. The totals of the population living above the threshold levels (row 2 and 3) are the results of the exposure analysis in section 4.

The last two rows of Table 3 give the overall results, expressed in additional health cases per 1000 vehicle-kilometres. The calculation for the case of column 1 (cars circulating at daytime) is as follows: Per one micro-dB, the number of additional cases would be 0.025 times 3.05, yielding 0.07625 cases. But according to row 1, 1000 car-kilometres during daytime cause an increase of only 0.050 micro-dB over the whole Swiss road network during one

Table 3: Determination of additional cases of communication and sleep disturbance in Switzerland, per 1000 vehicle-kilometres

	Daytime	Daytime	Night-time	Night-time
	Vehicle Type 1 (car, etc.)	**Vehicle Type 2 (truck, etc.)**	**Vehicle Type 1 (car, etc.)**	**Vehicle Type 2 (truck, etc.)**
DeltaLeq in micro-dB per 1,000 vehicle-km according to fate analysis	0.050	0.50	0.86	8.4
Million persons in Switzerland exposed to daytime LAeq ≥ 55 dB threshold	3.05	3.05		
Million persons in Switzerland exposed to night-time LAeq ≥ 46 dB threshold			3.36	3.36
Additional cases of disturbance per million persons caused by DeltaLeq 1 micro-dB according to effect analysis	0.025	0.025	0.017	0.017
Additional cases of communication disturbance per 1,000 vehicle-km in the daytime	0.0038	0.038		
Additional cases of sleep disturbance per 1,000 vehicle-km at night-time			0.049	0.48

year. Consequently, the number of sleep disturbance cases is 0.07625 times 0.050 micro-dB, or 0.0038 cases, as shown in column 1 of Table 3. We repeat here that the duration of a case is one year, because the disturbance lasts as long as the calculational noise increase, the latter being the DeltaLeq maintained during one year.

6 Damage Analysis in Detail

If we were satisfied with knowing the number of additional cases per 1000 vehicle-kilometres for each relevant type of health impairment, the last two rows of Table 3 would be the final result for the assessment of road traffic noise in Switzerland. But if we want to compare the damage to human health caused by night traffic with the corresponding damage of daytime circulation, or if we want to compare damage to human health due to vehicle noise to the corresponding damage due to vehicle exhaust gas, it is useful to express the severity of the health cases involved in a comprehensive system of health metrics.

As mentioned before, the choice was taken to use the 'DALY' health metrics system that was developed for the WHO (Murray 1996) and that is currently used by the WHO for reporting the annual world-wide damage to human health due to all kinds of causes, including environmental ones (WHO 2002:Annex Table 3). DALY (Disability Adjusted Life-Years) is a measure to express the amount of damage to human health, counting the number of life-years 'fully' lost due to premature death and the number of life-years 'partially lost' as a consequence of a disease or an accident ('disability'). Disability in comparison to death is weighted by means of 'disability weights' (DWs), which are recorded in tables for each disease category according to the severity of the associated impairment: Whilst one year lost by premature death has a DW of 1.0, one year lived with blindness gets a DW of 0.600 and one year lived with angina pectoris a DW of 0.227. The WHO tables of disability weights (Murray 1996:Annex Tables) have been developed through the co-operation of 9 regional panels of medical specialists and are designed for world-wide application. Hence, they are geared towards diseases occurring outside the developed industrial countries. This is why the WHO tables have been supplemented with studies conducted in the Netherlands (Stouthard 1997) and Australia (VGDHS 1999) focusing on medical conditions that are particularly characteristic of developed countries. However, sleep disturbance and communication disturbance could not be found in these published DW tables. For this reason, we organised a special investigation in Switzerland in order to obtain representative DWs for these two types of health impairment (Müller-Wenk 2002:46–50)

After a pre-test, a questionnaire was distributed in the year 2000 to the 64 members of the medical staff of the Swiss National Accident Insurance Institute (SUVA). This special group of physicians was selected because they have a broad professional experience in evaluating and comparing the severity of various disability situations caused by accidents. The questionnaire contained a table of disease conditions with the available Disability Weight DW issued by the sources mentioned above. These available DWs were put into ascending order. In addition, a circumscription of sleep disturbance and communication disturbance was supplied, matching the questions of the Swiss noise study 90 used in the effect analysis. The task given to the physicians was to insert sleep disturbance and communication disturbance at the adequate location into the sorted table of disease conditions with already existing DWs. This interpolation exercise was performed by 42 of the 64 physicians, and 41 of the 42 questionnaires returned could be used for the following analysis. The result thereof is shown in **Table 4**.

The disability weights of Table 4 express the panellists opinion that communication disturbance is roughly equally severe as 'mild to moderate asthma, symptom-free with or

Table 4: Disability weights for one year of sleep disturbance or communication disturbance, resulting from the panel exercise with physicians of the Swiss National Accident Insurance Institute SUVA

Condition	Disability Weight DW (95% Confidence Interval)
Communication disturbance during 1 year	0.033 (0.026;0.040)
Sleep disturbance during 1 year	0.055 (0.039;0.071)

Table 5: Health damage in DALY units per 1000 vehicle-kilometres on Swiss road network, during the day (DAY) or at night (NIGHT)

	DALY /1000 km DAY Vehicle type1 (car, van, light motorbike)	DALY /1000 km DAY Vehicle type 2 (truck, bus, heavy motorbike)	DALY /1000 km NIGHT Vehicle type 1 (car, van, light motorbike)	DALY /1000 km NIGHT Vehicle type 2 (truck bus heavy motorbike)
Communication disturbance	0.00013	0.0013		
Sleep disturbance			0.0027	0.026

without maintenance therapy', and that sleep disturbance is roughly equally severe as 'chronic hepatitis B infection without active viral replication'.

With the disability weights of Table 4, it is possible to express the health damage due to 1000 vehicle-kilometres in Switzerland in the generalised form of [DALY per 1000 vehicle-km]. This final result is shown in **Table 5**.

Considerations on uncertainty (Müller-Wenk 2002:52–56) lead to the conclusion that low estimates are roughly 50% of the Table 5 values, and high estimates roughly 200%.

7 Road Transport Outside of Switzerland

More and more, road-transport exceeds country borderlines. How can we treat international road transport showing up in LCA studies? Obviously, the concept presented here can be applied to the traffic and noise data of other countries: The basic data required per country are the annual vehicle-kilometres per vehicle class with a day/night split, the length of the national road network, and the population distribution with respect to road noise LAeq. It can be expected that the health damage per 1000 vehicle kilometres will be low for countries with low traffic density, and houses being well insulated and/or relatively distant from main roads. Until country-specific results are made available, we propose (Müller-Wenk 2002:60), as a very coarse temporary solution, to categorise European countries into average-noise, low-noise and high-noise countries: Spain and Slovakia belong to the high-noise group, Finland, Sweden and Denmark to the low-noise group, and the remaining countries to the average-noise group. It is proposed to use the Swiss figures (Table 3 and 5) for the countries of the average-noise group, to double these figures for the high-noise group and to divide them by two for the low-noise group.

8 Results and Discussion

The problem to solve is the following: According to the life-cycle inventory content or available supplementary information, 5500 kg of packaging material is to be transported by a 40-ton truck from the supplier to the food packer over an average distance of 500 km – how can the damage to human health due to the corresponding road noise be calculated? Assuming a daytime transport in a country comparable to Switzerland, the calculational damage due to the vehicle's journey is $0.038 \times 500/1000 = 0.019$ cases of communication disturbance (see Table 3) or $0.0013 \times 500/1000 = 0.00065$ DALY (see Table 5). The averaged net load (including empty sections) of a 40-ton truck can be set at 10800 kg (Maibach 1995:44) so that 50.9% of the damage caused by the vehicle can be allocated to the 5500 kg of our case. The result of the noise impact assessment is therefore 0.0095 cases of communication disturbance or 0.00033 DALY. If the truck travelled during the nighttime, the analogous calculation yields a damage allocatable to the 5500 kg of 0.12 cases of sleep disturbance or 0.0066 DALY.

Are these results reasonable? It is interesting to compare the health damage due to road noise in Switzerland – calculated according to the preceding sections – to other quantitative data on health damages.

The Swiss statistical yearbook (StatJB 2000:table T 14.4) specifies the number of life years lost in Switzerland in the year 1995 due to road traffic accidents at 12938 life-years or DALY. This figure contains life-years lost due to premature death only, and years are counted only up to the age of 70. If the life-years above age 70 and the life-years partially lost due to non-fatal road accidents were also counted, we might expect a figure of 20000–30000 DALYs for road accidents in 1995.

On the other hand, the number of DALYs due to road noise in 1995 in Switzerland can be estimated with the data of the preceding sections. The number of cases of sleep disturbance is roughly 13% of 3.36 million persons living above 45 dB road noise at night, equalling 436,800 cases (compare Fig. 4 for % disturbed, see Table 3 for population above threshold level). The number of cases of communication disturbance is roughly 19% of 3.05 million persons living above 54 dB during the day, equalling 579,500 cases. Multiplying the sleep disturbance figure with its disability weight of 0.055 and the communication disturbance figure with its DW of 0.033, the total health damage due to road noise in the year 1995 in Switzerland results in 43147 DALY.

This means that road traffic in Switzerland in 1995 caused a damage volume of 20000–30000 DALY due to traffic accidents and a damage volume of 40000 DALY due to road noise. Intuitively, we would have expected the damage from accidents to be higher than the damage from noise, but our feelings may be influenced by the high presence of road accidents in the media and the non-visibility of noise-related damage. Could the DALY figure for road noise be greatly exaggerated? Reviewing the key figures of population living above the threshold noise levels, the number of sleep/com-

Table 6: Comparison of DALYs (normalised to population size 7.08 million persons) between The Netherlands (De Hollander 1999) and Switzerland (Müller-Wenk)

		De Hollander (NL figures adapted to size of Swiss population)	**Müller-Wenk**
Severe annoyance (communication disturbance)	**Persons affected**	**803000**	**579500**
	Disability Weight used	0.01	0.033
	Total DALYs	8045	19129
	DALYs (low – high)	(2368–14577)	(9561–38247)
Sleep disturbance	**Persons affected**	468000	436800
	Disability Weight used	0.01	0.055
	Total DALYs	4995	24024
	DALYs (low – high)	(976–9654)	(12012–48048)
Traffic accidents	Total DALYs	33894	20000-30000

munication cases per 100 persons living above threshold levels, and the DWs for the two types of disturbance, we do not find room for substantial errors: Our noise-level-distribution of the population coincides reasonably well with other Swiss data and with figures for comparable European states. The slope of the dose-effect characteristics used here for sleep disturbance and communication disturbance is comparatively steep, but not excessive in comparison to other social surveys. And the disability weights developed by the physicians' panel may be somewhat high, but could not be set very much lower compared with other low-level disabilities of the DW-catalogue currently used by the WHO. We therefore conclude that it is not inadequate to state that the importance of noise damages due to road traffic in Switzerland is similar to the importance of road accidents.

A further comparison of our results is possible with calculations from the Netherlands (De Hollander 1999). The Netherlands and Switzerland are countries of reasonably comparable structure, whereby the population of NL is 2.2 times larger than the Swiss population. De Hollander gives figures for noise related 'severe annoyance' and 'sleep disturbance' (whereby noise includes not only road noise) and the definitions of the disturbances may be different from those we used in Switzerland. Nevertheless, the comparison of the results in **Table 6** is quite interesting.

Assuming that road traffic is the dominant source of noise also under Dutch conditions, it is apparent that the main difference between De Hollander's and Müller-Wenk's figures stem from the disability weights. Unfortunately, the efforts to obtain details on the origin of de Hollander's disability weights and other background data have not been successful so far. Consequently, the provisional result of the comparison is that the data of the two studies are not contradictory, except for the disability weights. Irrespective of this open point, it can be stated that both studies come to the conclusion that the damage in DALY units of road traffic accidents and of road traffic noise effects are of the same order of magnitude.

9 Conclusions and Outlook

The health damage caused by road vehicle noise is so important that LCA studies involving non-negligible road transport volumes are clearly incomplete if the noise effects are neglected. The method proposed here can be used immediately in LCA practice, and LCI data should be prepared in such way that road transport noise assessment can be executed according to this method. For Swiss conditions, the method appears to be adequate, but for other countries it has as yet not been worked out in detail. Although a provisional adaptation of the results to other European countries is proposed here, it is desirable to undertake additional efforts to collect basic data on road traffic noise at the individual country level, and to continue and broaden the conceptional work on road noise assessment.

Rail transport is sometimes an alternative to road transport, and LCA may be used to justify a decision 'rail or road' from an environmental point of view. In analogy to the solution proposed here for road traffic noise, the life-cycle assessment of rail transport noise can be developed as follows: A rail transport from A to B is considered to be using a fraction of the transport capacity of one additional freight train on the network segments connecting points A and B: as rail networks are much wider meshed than road networks, the exact routing of a rail transport is better known than that of road transport. On the basis of data on the number of persons per noise level LAeq along each segment of the rail network, the results of the fate and exposure analysis can be obtained easily: These results consist in the DeltaLeq for the fraction of one additional train used by the transport, as well as the current rail noise distribution of the population along the rail network segments used. The effect analysis of rail noise should reflect the fact that – compared to road transports – the noise pattern of railway lines contains less noise events per day, so that the momentaneous noise level deviates more from the average Leq than in the case of roads. This means that the effect analysis of railway noise should be based on rail-specific dose-effect characteristics which can be found in primary studies being listed and charted in (Miedema 1998).

Information on types and magnitude of health effects depending on noise levels is still a weak point of transport noise impact analysis. Until now, social surveys generally focus on annoyance and do not indicate noise effects in terms of the medical diagnosis type. This, in spite of the fact that transport noise is now clearly recognised to cause observable health effects in the persons affected. Further, the available medical studies on noise effects are difficult to compare because they express noise levels in varying units (Leq, Lmax or SEL) which are not easily convertible. As all of these three noise measures have their merits, chances are poor that researchers will agree on a best unit. It is therefore desirable that medical studies indicate how the noise units they use can be converted to the other units mentioned above in the context of the respective study, so that a pooling of study results is facilitated.

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Noise Assessment in LCA – A Methodology Attempt:

A Case Study with Various Means of Transportation on a Set Trip

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This paper focuses on impact assessment of noise disturbance in the framework of LCA studies.

A number of difficulties arose in the course of the study, namely expressing noise measurements in an easy-to-handle unit, importing disturbance engendered by several simultaneous sources to every single course, handling additive quantities non linearly, taking into account the space and time dependence of potential impacts associated with noise.

It is shown how all these issues were tackled in an LCA study that assessed different modes of transportation. The methodology developed takes into account the disturbance to noise level, exceeding a set threshold and no other kinds of noise effects.

It is obvious that disturbance due to noise emission depends on people density in the neighborhood of the emission source. In this context, a 'site-dependent approach' was taken, meaning that we did include local factors into the valuation. The methodology developed in this article may be extended to other types of emissions when it is necessary to integrate local factors in the assessment phase of LCA.